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ENERGY REDUCTION IMPLICATIONS WITH FENESTRATION

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SUMMARY

Johnson, Arasteh, Selkowitz: Energy Reduction Implications with Fenestration. In this paper we discuss results from a number of parametric analyses of the energy and cost influences of fenestration in a prototypical office building. The energy important parameters of fenestration, daylighting, and electric lighting were systematically varied in several climates using the DOE-2.1 energy simulation program to determine net annual results. Results are presented for two climate extremes; one heating-load dominated and the other cooling-load dominated. The increase or decrease of net annual energy consumption and peak electrical demand due to fenestration is demonstrated. Daylighting, is shown to be the single most important strategy to reduce energy use, but can be an energy and cost liability. Conditions under which these liabilities occur are discussed, and optimal design solutions for minimizing energy costs are suggested.

RESUME

Johnson, Arasteh, Selkowitz: Influences des fenêtres sur la consommation d'énergie. Ce rapport présente les résultants de plusieurs analyses paramétrieques sur l'influence des fenêtres dans un batiment tertiaire, en termes de consommation et coût d'énergie. L'utilisation du programme de simulation DOE-2.1 a permis d'étudier la sensibilité des résultats énergétiques annuels, aux paramètres importants liés aux fenêtres, à l' éclairage naturel et électrique. Des résultats sont présentés pour deux climats extrêmes: prédominance soit du chauffage, soit de la climatisation. On observe une variation (positive ou négative) de la cosommation annuelle et de la demande d'énergie, dûe aux paramètres des fenêtres. L'éclairage naturel semble la stratégie la plus adaptée pour réduire la consommation d'énergie mais son usage peut être délicat et coûteux: à cet effet, différentes configurations sont présentées et des solutions visant à un coût minimum sont suggerées.

KURZFASSUNG

Johnson, Arasteh, Selkowitz: Parameterstudie ueber die Energieeinfluesse von Fenstern. In diesem Artikel werden die Ergebnisse einer Anzahl von Analysen ueber die Energie-und Kosteneinfluesse von Fenstern in einem standardisiertem Buerogebaeude diskutiert. Die fuer die Fensterstudie wichtigsten Parameter, Tageslicht und kuenstliche Beleuchtung, wurden fuer unterschiedliche Klimata systematisch variiert. Fuer die Simulationen wurde das Gebaeudesimulationsprogramm DOE-2.1 zur Bestimmung der jaehrlichen Energieverbraeuche herangezogen. Die Ergebnisse wurden fuer zwei extreme Klimata durchgefuehrt; eines mit vorherrschendem Heizenergieverbraeuch, das andere mit beherrschendem Kuehlenergieverbrauch. Die Unterschiede des jaehrlichen Netto-Energieverbrauchs und der Spitzenlast infolge unterschiedlicher Fensterauslegungskriterien werden dargestellt. Tageslicht ist der wichtigste Einflussfaktor fuer Energieeinsparung, wenn auch unter Umstaenden nicht der kostenguenstigste. Die Bedingungen, unter denen diese Faelle eintreten koennen, werden erlaeutert und optimale Auslegungsanleitungen fuer die Minimierung der Energiekosten werden vorgeschlagen.

ENERGY REDUCTION IMPLICATIONS WITH FENESTRATION

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This paper discusses results from a number of office building parametric studies in which we systematically varied fenestration and electric lighting variables in specific climates. Results demonstrate that properly designed and managed fenestration in office buildings can reduce costs for energy consumption and electrical peak demand and may reduce chiller requirements.

Methodology

Our office building model consists of four identical perimeter zones, each 4.8 m deep, surrounding a common core. The ceiling and floor were modeled as adiabatic surfaces (no net heat transfer), limiting envelope thermal transfer to the walls and fenestration. Overall thermal conductance was held constant as glass area was varied, isolating solar gain and daylighting effects. Fenestration thermal conductance, glazing area, visible transmittance, and shading coefficient were varied. Use of shades for visual or thermal comfort was assumed. Electric lighting was varied from 7.5 to 29.1 W/m^2, based on a design illuminance of 538 lux. For daylighted cases, electric lighting output was reduced uniformly in response to daylight. The DOE-2.1B building energy analysis program [1] was the modeling tool. A detailed description of the building model appears elsewhere [2,3]. To better understand the influence of fenestration on results, we define a lumped parameter which we call effective aperture. This parameter is the product of the ratio of glass area to wall area times the visible transmittance of the glass.

Results

Cold climate energy use

Total annual energy consumption for a south zone in Madison, WI is plotted against effective aperture in Fig. 1. The solid lines represent an electric lighting schedule that follows an occupancy schedule without regard to daylight levels. The dashed lines represent operation with the same schedule but with electric light dimming in response to daylight. This cold (Lat. 43.1°N) climate heating season (4176°C HDD at base 18°C) can use solar gain to offset heating loads, but during summer months solar gain is a cooling load.

With thermal conduction losses held constant (U = 0.97 $W/m^2 {}^oC$) and without daylighting controls, even at the highest lighting power density studied (29.1 W/m^2), fenestration up to an effective aperture of about 0.10 produces net energy benefits in the south zone. At larger effective apertures the added solar gain plus the high internal load produces an energy penalty. As electric lighting's internal load diminishes, more solar gain offsets heating load, and minimum energy consumption occurs at larger effective apertures.

When daylighting is integrated into the system, annual energy consumption falls off as effective aperture increases up to a limit beyond which it levels off. Daylighting diminishes the internal load from electric lighting, and solar gain offsets more of the heating load. The negative impact of summer solar gain is mitigated by lowered internal gains from electric lighting.

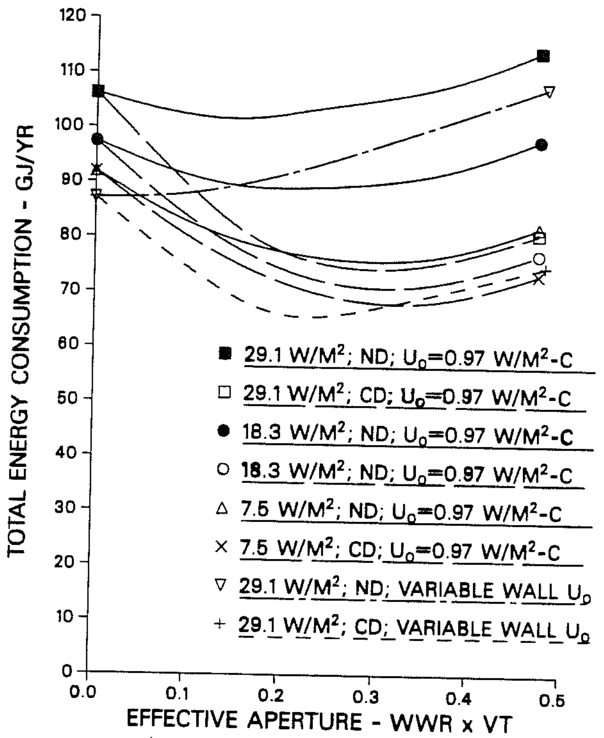

Figure 1 Total annual energy consumption for south zone (139.4 m^2) in Madison WI.

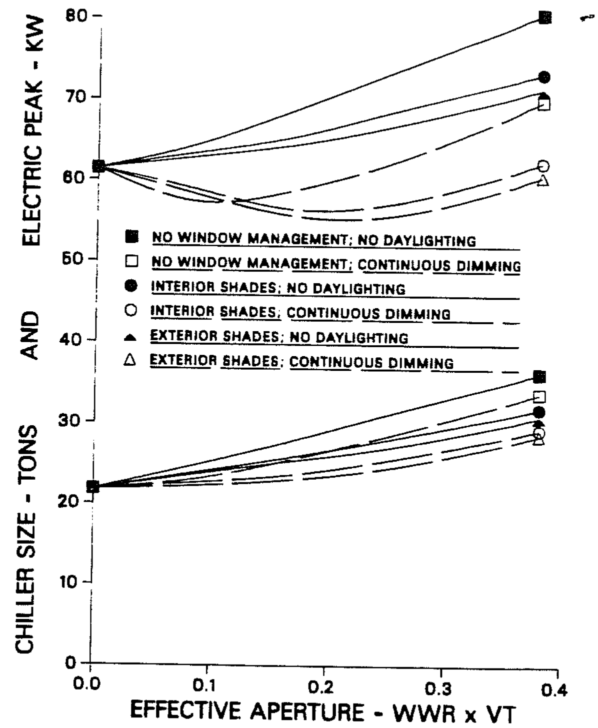

Figure 2 Chiller size and peak demand for entire module (1,486 m^2) in Madison WI.

The high heating loads in this climate impose the need to control thermal losses. The low insulating value of glass typically reduces the overall thermal resistance and compromises the benefits just demonstrated. Figure 1 shows the effect of reducing the conductance of a well-insulated wall ($U = 0.57$ W/m^2 ^{o}C) by increasing glass ($U = 2.2$ W/m^2 ^{o}C) area. Without daylighting adding glass lowers energy performance by increasing winter thermal losses and summer solar gains. Using daylighting, however, provides minimum energy consumption. The minimum occurs at a smaller effective aperture because with better control of thermal loss less solar gain is beneficial.

For the north zone with fixed overall conductance in Madison, annual energy consumption in the nondaylighted case steadily decreases with increasing aperture; with daylighting it decreases more rapidly. When thermal losses are controlled, north fenestration can provide net energy benefits. These results suggest the importance of glazing materials having low thermal conductivity and high visible transmittance. When overall thermal resistance declines with increasing glass area, net annual energy consumption without daylighting goes up, but with daylighting performs better than an opaque wall.

Cold climate peak electrical demand

With our model's gas-fired boiler and electric chiller, peak electrical demand is a summer phenomenon. In Fig. 2 coincident peak demand for the entire module is plotted as a function of effective aperture for a lighting power of 18.3 W/m^2. Daylighted and nondaylighted conditions with and without window shade management are shown. The solar gain admitted by fenestration imposes cooling load and peak demand increases with effective aperture. Daylighting, by reducing electric lighting, reduces peak demand to below that for an opaque wall. Compared to the nondaylighted case with identical glazing, this reduction reaches approximately 20% with 37.5% of the floor space daylighted. The reduction would increase with more daylighted space. Peak demand in the unmanaged window case is substantially higher, indicating the importance of solar control.

Hot climate energy use

In Fig. 3 results for a north zone in Lake Charles, LA are shown. In this cooling-load dominated climate (Lat. 30.1^{o}N, 1051^{o}C HDD at base 18^{o}C) fenestration, without daylighting, imposes an energy penalty. With daylighting, windows provide net energy benefits, and energy consumption is minimized within the effective aperture range 0.15 to 0.20. Larger effective apertures provide more daylighting but increases net energy consumption.

Hot climate peak electrical demand

Since peak electrical demand in both climates occurs during the summer peak cooling season the implications discussed above for Madison also apply to Lake Charles with solar gain control being an even more critical concern.

Daylighting efficacy

It is generally assumed that because the luminous efficacy of daylight (100 - 120 lumens/watt) is greater than that of typical fluorescent systems (60-90 lumens/watt), daylighting will reduce cooling loads relative to electric lighting. This assumption ignores the details of light distribution within a room and the difference between total admitted flux and the fraction received at the work surface. When these factors are accounted for, the advantage of daylight as a cooler source of light is compromised by the nonuniform daylight distribution typical of a sidelighted office space. Figure 4 compares annual cooling loads from skylights and vertical fenestration. The more uniform flux distribution with the skylight system reduces cooling load as daylight displaces electric light up to a daylight saturation level. Daylight is delivering light with higher luminous efficacy than the electric lighting. In the case of vertical fenestration, cooling load decreases only at high lighting power density. At lower power densities the cooling load of daylighting increases relative to electric lighting, indicating a lower effective luminous efficacy for daylight.

Cooling equipment

While fenestration can provide the benefits of reductions in energy requirements and peak electrical demand it may impose penalties on cooling equipment sizes. Peak cooling load, occurring during summer conditions of coincident high ambient temperature and solar gain, is the usual criterion for sizing chillers and associated cooling equipment. Chiller size (Fig. 2) increases continuously with effective aperture, but daylighting reduces chiller size compared to the same fenestration without daylighting. These results are consistent with Fig. 4, which shows cooling energy increasing with effective aperture for an installed power density of 18.3 W/m^2.

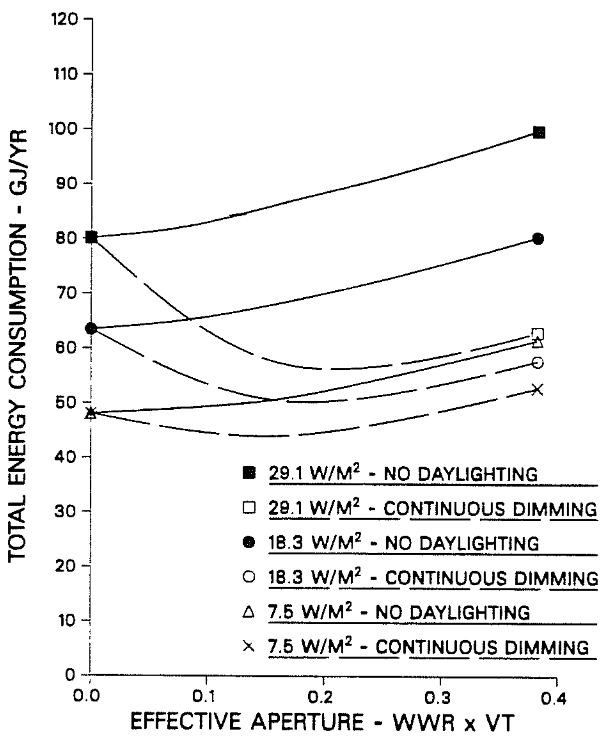

Figure 3 Total annual energy consumption for north zone (139.4 m^2) in Lake Charles LA.

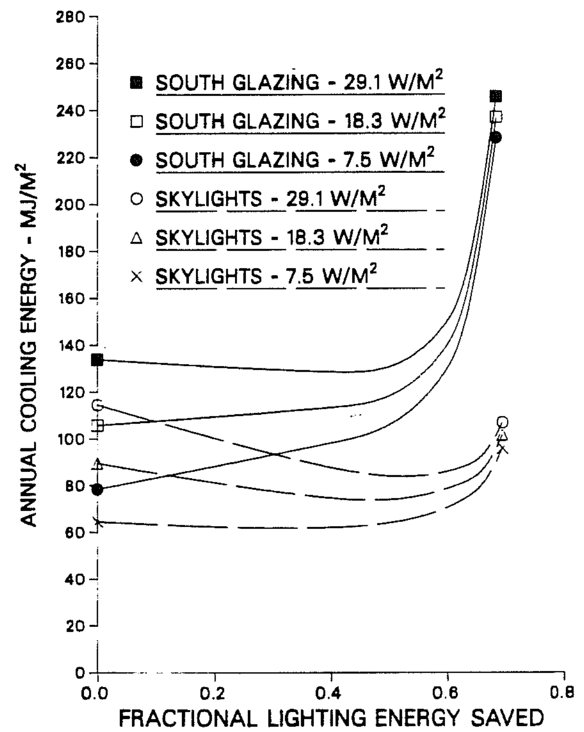

Figure 4 Cooling energy per unit floor area of daylighted space as a function of electric lighting savings in Lake Charles LA.

Cost implications

The integrated design of fenestration and lighting systems in which solar gain is controlled, daylight is admitted, and electric lights are dimmed in response to daylight levels will reduce net annual energy consumption and peak electrical demand. These reductions lower operating costs over the life of the building. The magnitude of the savings will depend on the specifics of building design, climate, heating fuel costs, and utility rate structure. To realize these savings typically requires added first cost for electric lighting dimming control systems. In the United States these systems presently cost about \$12/m^2 of floor area. These first costs may, however, be offset by reductions in chiller and cooling equipment costs. In Madison with 18.3 W/m^2 lighting power density, an effective aperture of 0.2 and managed shades, daylighting reduces chiller requirements by about 3 tons. At \$2000/ton for cooling equipment, this is a cost reduction of \$11/m^2 of floor area, which is about equal to the cost of the lighting control system.

Summary and Conclusions

With proper design and operation, daylighting and solar control, fenestration can provide energy and cost benefits. Extensive parametric simulation results suggest the following generalizations:

1. For each climate, orientation, and lighting power density there is an optimum effective aperture for minimum net annual energy consumption. Larger effective apertures diminish the benefits because of increasing cooling load.

2. Daylighting strategies can reduce peak electrical demand by substantially reducing the electric lighting component of peak demand.

3. Solar gains must be controlled to mitigate potential negative influences of fenestration on energy consumption and chiller size. The benefits of daylighting strategies can be negated if solar gain is not controlled.

4. The luminous efficacy of daylight is greater than that of fluorescent light, but it may not be a "cooler" light source. Daylight's efficacy will depend on solar controls, luminous flux distribution in the space, and electric lighting control system response to that distribution.

These conclusions are sensitive to variations in climate, orientation, and modeling assumptions. Results may differ for building configurations, operating systems, and operating schedules other than those modeled.

Acknowledgements

This paper presents selected results from a series of parametric modeling studies. Results of these studies are discussed in greater detail in the referenced papers and others available from the authors. This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. Portions of this work were supported by Battelle Pacific Northwest Laboratory.

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COST EFFECTIVE LIGHTING

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COST EFFECTIVE LIGHTING

ABSTRACT

Long-life replacement lamps for the incandescent lamp have been evaluated with regard to their cost effectiveness. The replacements include the use of energy buttons that extend lamp life as well as an adaptive fluorescent circline lamp that will fit into existing incandescent lamp sockets. The initial, operating, and replacement costs for one million lumen-hours are determined for each lamp system. We find the most important lighting cost component is the operating cost. Using lamps that are less efficient or devices that cause lamps to operate less efficiently are not cost-effective. The adaptive fluorescent circline lamp, even at an initial cost of $15.00, is the most cost effective source of illumination compared to the incandescent lamp and lamp systems examined.

1. INTRODUCTION

Industrial, commercial and residential consumers have been trying to reduce spiraling costs by lowering their energy consumption, one of the major contributors to these increases. Lighting is one area that is being scrutinized, particularly in spaces that have been over-illuminated.

One current vogue of amending the illumination excess has been to remove lamps as well as replace existing fixtures with lower wattage lamps. Toward this end, the lamp industry has produced incandescent lamp replacements that use less energy, provide less illumination and extend lamp life. The longer lamp life helps to reduce the labor cost of replacing lamps that are in continuous use and require frequent replacement. This report is concerned with the relative merits of these products.

We will discuss seven systems in this report:

* 100W, 120V incandescent lamp,
* 100W, 130V incandescent lamp,
* 100W, long-life incandescent lamp,
* 100W, 120V incandescent lamp with a thermistor energy button,
* 100W, 120V incandescent lamp with a diode energy button,
* 65W, 120V incandescent lamp with a heat reflecting layer on the glass envelope, and
* 44W, 120V fluorescent circline replacement lamp.

Some of these units may be unfamiliar, and will be explained briefly.

Energy buttons are placed into light bulb sockets (Edison sockets) and the lamp inserted into the socket over the button. This is schematically illustrated in Figure 1, which also shows the circuit diagram where the button is in series with the lamp. The energy buttons use either one of two types of solid-state devices.

One type of device is a thermistor. At room temperature the thermistor has high resistance and its resistance decreases as the thermistor's temperature increases. When the lamp is turned on, the initial current is less than the operating current because the thermistor's resistance is high. After several minutes the circuit current heats the thermistor, reducing its resistance, and the circuit current increases. The lamp then operates near its normal light output. Energy button manufacturers contend that starting incandescent lamps in this manner extends the lamp life by a factor of four.

The second type of energy button device is a diode. The diode device rectifies the 60 Hz input power, reducing the power available to the lamp by about one-half. This lowers the filament temperature of the lamp, thus reducing the light output and extending lamp life.

In the following sections we will review the performance of these long-life light bulbs and measure the performance of incandescent lamps with and without energy buttons. We will analyze the total cost of all these light sources by considering the initial cost, the operating cost and the replacement labor cost. This result will assist consumers in selecting the most cost-effective light source suitable for their needs.

2. MEASUREMENTS

The performance of a light source is determined by measuring the input power supplied to the lamp or lamp system and the total light flux radiated by the lamp. Efficacy is the figure of merit and is defined as the ratio of the light flux to the input power (lumens per watt). One standard method used to measure the total light flux from a light source is with an integrating sphere and a standard light source with a known light output. In this study we have used an integrating light chamber to determine the light flux from the lamps. We have employed a 100 watt incandescent lamp as a standard (rated light output = 1750 lumens), and measured the relative changes of other lamps with respect to this lamp.

Estimating the relative light output of two light sources with the naked eye will give an erroneous result because the eye is sensitive only to brightness differences (contrast), not the amount of light.

The electrical input (power, voltage and current) to each lamp and lamp system was measured at the same time the light flux was measured in the integrating chamber. To obtain the the most reliable results, the same 100 watt incandescent lamp that was used as the standard was also used with the energy button. Thus, the relative changes in the efficacy with and without the button will be accurate.

We are also interested in identifying any potential safety hazard and have measured the socket temperature of the 100 watt lamp with and without the thermistor type of energy device.

3. RESULTS

3.1 Performance

In table 3.1 we present the results of our input-output measurements for the 100 watt lamp, the 100 watt lamp with each type of energy button, a 100 watt (130 volt) lamp, a 100 watt long-life lamp, a 65 watt lamp with a heat reflective coating and an adaptive circline fluorescent lamp. The adaptive circline fluorescent lamp can be inserted into the same Edison socket that is used for the incandescent lamp.

The results show that the diode type energy buttons reduce the input power to the 100 watt incandescent lamp by 42 percent; however, the lamp light output decreases by 74 percent. The lamp efficacy is the best figure of merit to assess the lamp's performance. Note that all the long-life lamp systems operate at efficacies less than the 100 watt lamp, and the system efficacy for the adaptive circline fluorescent lamp is 39.8 lumens per watt.

The 65 watt lamp has a heat reflective coating on the glass envelope. This selective coating transmits visible light and reflects infrared radiation back to the filament. This recirculated heat allows the filament to maintain operating temperature with less supplied power. This lamp produces 1450 lumens with 65 watts input for a 22.3 lumens per watt efficacy.

TABLE 3.1 Lamp Performance

	Lamp Type						
	100W Lamp	100W Lamp (130V)	100W Lamp (long life)	100W Lamp (diode)	100W Lamp (therm)	65W Lamp (heat reflect)	Fluorescent Lamp (adaptive)
Input Voltage (volts)	120	120	120	120	120	120	120
Current (amps)	.833	.750	.833	.705	.832	.783	.560
Power (watts)	100	90	100	58.5	100	65	44
Output Light (lm)	1750	1350	1490	490	1600	1450	1750
Change Output Lt. (%)*	0	-23	-15	-73	-10	-17	0
Efficacy (lm/wt)	17.5	15.0	14.9	8.4	16.0	22.3	39.8
Change in Efficacy (%)*	0	-14	-15	-52	-9	+27	+127

*Relative change with respect to 100 watt lamp

3.2 Socket Temperature

Table 3.2 lists the measured socket temperature for the 100 watt incandescent lamp and the same lamp with the thermistor type energy button. The energy button heats up when current is flowing and we find that the bulb socket temperature reaches 105°C, compared with 48°C for the 100 watt incandescent lamp without an energy button.

TABLE 3.2 Socket Temperature

Lamp Type	Socket Temperature*
100 watt lamp	48°C
100 watt lamp (with thermistor)	105°C

* Ambient temperature 22°C

4. LAMP LIFE, EFFICACY, COLOR

The results of our measurements can be understood by a brief description of the physics of the incandescent lamp. The incandescent lamp is an inefficient source of visible radiation since only a small portion of the emitted radiation is in the visible region. Most of the emitted radiation is in the lower energy portion, the near infrared. When the filament temperature is lowered, the entire emitted spectrum shifts toward lower energy. There is a greater relative decrease of the radiation in the visible region, thus, the lamp efficacy (efficiency of transforming the electrical energy into light) will decrease. Because of the above shift in the spectrum for the lower filament temperature, the color of the lamp will appear more reddish. The new compact fluorescent lamps employ phosphors which make them virtually indistinguishable from incandescent lamps.

Lamp filaments eventually fail by the evaporation of the metal and subsequent disintegration of the filament coils. Lamps operating at lower filament temperature have a slower evaporation rate, thus such filaments should have an extended life. However, filaments also become brittle as they operate and become increasingly sensitive to physical shock and vibration. A lamp may fail, therefore, long before its expected life due to its mechanical environment rather than because of filament evaporation. In addition to operating filaments at a lower temperature, commercial long-life lamps are filled with a heavier gas (krypton) that also inhibits the filament evaporation rate.

The above description is consistent with our measurements which show that a 40 percent power decrease results in a 75 percent light output decrease for an incandescent lamp. This is contrary to some of the published information by some of the energy button manufacturers which shows that the input power and light output decrease by the same proportion.

5. COST OF LIGHT SOURCE

To assess the true cost of a light source, one must evaluate the lamp performance. One metric to assess the relative merits of light sources is to determine the cost with respect to a specific number of lumen hours (luminous energy). That is, we must remember when we buy a lamp that we are purchasing illumination (light), and once the lamp is purchased, we are committed to the cost of putting the lamp in the socket and the cost of energy until it fails. Thus, we must compare costs on a "per unit of light" basis. In the following sections we will discuss the cost of lamps with respect to one million lumen hours (10^6 lm-hrs) of light.

5.1 Lamp Life

One expression for estimating incandescent lamp life operated at different voltages is the following:

$$\left(\frac{L_1}{L_o}\right) = \left(\frac{V_o}{V_1}\right)^{13} \qquad (1)$$

where L_0 and V_0 are the rated lamp life and operating voltage, respectively, and L_1 is the lamp life when it is operated at voltage V_1.

In Table 5.1 we list the rated and operating voltages of six light sources. For the lamps in the first four columns we have used the expression (1) to calculated the approximated lamp life with with respect to the 100 watt lamp L_0 (L_0 = 750 hours).

The effective lamp voltage used for the diode energy button (83 volts) was obtained by dividing the measured power by the measured current (58.5 watts/.705 amps = 83 volts). Since the relative lamp lives for the long-life incandescent and the fluorescent lamp are not based upon the operating voltage rating, we have used the manufacturer's rated life. The long-life lamp is rated to operate at 120 volts, but its life is extended by the use of a thicker, heavier filament and back-filling the lamp with a heavy krypton gas.

TABLE 5.1 Lamp Life

	Lamp Type						
	100W Lamp	100W Lamp (130 volt)	100W Lamp (therm.)	100W Lamp (diode)	100W Lamp (long life)	EELB	Fluor. Lamp
Rated Voltage (volts)	120	130	120	120	120	120	120
Operating Lamp. Vltg. (volts)	120	120	115.8	83	120	83	120
Lamp Life (relative)*	1.00	2.82	1.59 (1.62)[1]	122 (50)[1]	3.33	3.33	13.33
Lamp Life (hours)	750	2115	1215	37,500***	2,500**	2,500**	7,500**

1 See text for explanation.
* Relative to 100 watt lamp.
** Manufacturer rated life.
*** The theoretical value of life ratings become progressively less reliable once incandescent lamps are operated below 90% of their rated voltage.

The estimate relative life of the lamp with the thermistor type energy button is calculated to be 1.59 times longer than without the button. This is based on the lamp operating at 4.2 volts less due to the voltage drop across the thermistor. The button manufacturers claim that life is extended by turning on the lamp at a lower initial current. There is no evidence presented to substantiate these claims. It is possible that lamp life is slightly extended by this "softer" start near end of life when the filament is highly stressed. Due to this uncertainty we arbitrarily extend by 2% the estimated lamp life calculated from equation (1). We will assume that the thermistor energy button extends the incandescent lamp life by a factor of 1.62.

The theoretical extension of lamp life with the diode energy button of 122 times the normal lamp life is extremely long (750 x 122 = 91,500 hours). Even in the most intensively used areas (≈4,000 hours per year), a light bulb would last twenty years.. This long life is difficult to substantiate. Furthermore, for such a long life, other factors would become effective in limiting lamp life, e.g., gas leakage, thermal stresses, material aging, accidental breakage, filament fatigue and filament failure from constant vibrations. Thus, we will assume that the diode energy button will extend the lamp life by a factor of fifty.

5.2 Lamp Cost per One Million Lumen Hours

Table 5.2 lists the initial product cost for the lamps and the energy button. The prices are those specified by their manufacturer. The two prices listed for the diode type energy button are obtained from two manufacturers. We will assume an energy button will last for five lamps. They should last forever, but there will be losses during the installation, etc. The fourth column lists the unit cost for each type of light source. The final column lists the initial cost for each system for one million lumen-hours.

TABLE 5.2 Initial Production Cost

Lamp Type	Lamp (unit)	Energy Button Unit	Energy Button Per Lamp[1]	System Cost Per 10^6 lm-hrs.
100 watt	$0.70	$0.00	$0.00	0.53
100 watt (130 volt)	0.70	0.00	0.00	0.25
100 watt (thermistor)	0.70	2.00	0.40	0.57
100 watt (diode)	0.70	2.00[2]	0.40	0.06
100 watt (diode)		6.00[2]	1.20	0.103
100 watt (long life)	0.83	0.00	0.00	0.22
65 watt (head reflector)	9.00	0.00	0.00	2.48
Fluorescent (lamp and ballast Combination)	15.00	0.00	0.00	1.14

[1] Assume that an energy button will last 5 amp lives.
[2] Two different costs from two different manufacturers.

This is calculated from the following expression:

$$\text{Cost per } 10^6 \text{ lm-hrs} = \frac{\text{Unit Cost (\$)}}{\text{Light Output (lm)} \times \text{Life (hrs)}} \times 10^6 \qquad (2)$$

where life = 750 hours x relative lamp life (see Table 5.1). Note that the additional cost for the diode energy button is only about two cents since the lamp life is so long. Thus, the assumption that the buttons last for five lamps is not of significance. The table shows that the initial cost per 10^6 lumen hours of the 65 watt lamp and the fluorescent circline lamp are the highest. The initial cost of the 100 watt, 130 volt lamp, the 100 watt long-life lamp and the 100 watt lamp with the diode energy button are the lowest.

5.2.1 Operating Cost

Table 5.3 lists the operating cost of each of the six lamp systems considered in this report. The operating cost per one million lumen hours is obtained from the following expression:

Operating cost per 10^6 lm-hrs

$$= \frac{\text{Power (watts) x Energy Cost (\$/w-hr)}}{\text{Light Output (lumens)}} \times 10^6 \qquad (3)$$

$$= \frac{\text{Energy Cost}}{\dfrac{\text{Light Output}}{\text{Power}}} \times 10^6$$

Note that the operating cost of any light source depends only upon the cost of energy and the efficacy of the lamp system. The highest operating cost is obtained for the 100 watt lamp operated with the diode energy button. The lowest operating cost is for the fluorescent circline system.

TABLE 5.3 Operating Cost*

	Power (watts)	Light (lumens)	Cost Per 10^6 lm-hrs.
100 watt	100	1750	$4.57
100 watt (130 volt)	90	1350	5.33
100 watt (thermistor)	100	1600	5.00
100 watt (diode)	58.5	490	9.55
100 watt (long life)	100	1490	5.37
65 watt (heat reflector)	65	1450	3.59
Fluorescent	44	1750	2.01

* Energy cost at $0.08 per kilowatt-hour.

5.2.2 Labor Replacement Cost

The cost of replacing an incandescent lamp can vary considerably. In the home, the cost of replacement will be virtually nil, while in the commercial and industrial sectors a typical cost is about one dollar. However, there are some special locations where lamp change costs can reach several dollars. Manufacturers of long-life lamps and lamp systems (energy buttons) cite costs as high a $15.00. In Table 5.4 we have accommodated all of the claims by determining the labor replacement cost per one million lumen hours for a replacement cost from $0.10 to $15.00 for each change. This has been calculated from the expression:

Replacement Cost per 10^6 lm-hrs

$$= \frac{\text{Cost of One Change (\$)}}{\text{Light Output (lumens) x Lamp Life (hours)}} \times 10^6 \qquad (4)$$

The results clearly show that the maintenance cost per million lumen hours is least for the longer life lamps.

TABLE 5.4 Labor Replacement Cost

lm-hrs.	Lamp Changes Change	---------Cost of Change Per 10^6 lm-hrs.---------- $0.10 Per Change	$1.00 Per Change	$5.00 Per Change	$15.00 Per 10^6
100 watt	.762	.08	.76	3.81	11.43
100 watt (130 volt)	.350	.04	.35	1.75	5.25
100 watt (thermistor)	.514	.05	.51	2.57	7.71
100 watt (diode)	.0544	.01	.05	0.27	0.82
100 watt (long life)	.268	.03	.27	1.34	4.02
65 watt (heat reflector)	.276	.03	.28	1.38	4.14
Fluorescent	.076	.01	.08	0.38	1.14

5.2.3 Total Cost

Table 5.5 lists the total cost of the seven lamp systems by summing the three component costs. In the table there is a range of costs depending upon the labor cost of each change. The table clearly shows that operating cost primarily determines the cost of illumination . That is, for most lamp systems, at least one half of the total cost is the operating cost. For replacement costs of ten cents, the 100 watt lamp is the most cost effective of the incandescent lamps. For replacement costs of one dollar, there is little difference in cost between a one hundred watt lamp and the long-life lamp. The lamp with the diode energy button has a high operating cost of $9.55 per million lumen hours, which overshadows its very low initial and replacement cost. The most cost-effective incandescent lamp system is the 100 watt, long-life lamp in applications where the cost to change lamps is more than $1.00.

The 65 watt heat reflector lamp is 27% more efficient than the 100 watt lamp and lasts 2500 hours, but these improvements are not enough to offset the high initial product cost.

The most interesting outcome of this comparison of light sources is the extraordinarily low cost of the adaptive fluorescent circline lamp system. Even for the relatively high initial unit cost of $15.00, the total cost of this light source is less than one half the cost of most of the alternatives considered in this report for all of the replacement costs.

TABLE 5.5 Total Cost

	Initial ($) Per 10^6 lm-hrs.	Operating ($) Per 10^6 lm-hrs.	Total Cost Per 10^6 lm-hrs. $0.10 Per Change	$1.00 Per Change	$5.00 Per Change	$15.00 Per Change
100 watt	.53	4.57	5.18	5.86	8.91	16.53
100 watt (130 volt)	.25	5.33	5.62	5.93	7.33	10.83
100 watt (thermistor)	.57	5.00	5.62	6.08	8.14	13.28
100 watt (diode)	.08 [1]	9.55	9.64	9.68	9.90	10.45
100 watt (long life)	.22	5.37	5.62	5.86	6.93	9.61
65 watt (heat reflector)	2.48	3.59	6.10	6.35	7.45	10.21
Fluorescent	1.14	2.01	3.03	3.10	3.42	4.22

[1] Based on average diode energy button cost.

6. SAFETY

The energy button presents a potential safety hazard both in its installation and during operation.

The manner in which the energy button is installed poses a potential shock hazard. Since the installer is not certain whether the electrical power is off or on, he may be subject to a serious shock. Granted, it is due to the installer's carelessness, but one is still subject to injury. In addition, Edison sockets that are horizontal, or burn lamps base up, pose a further installation difficulty.

In many sockets, some of the energy buttons limit the depth at which the lamp can be inserted. Thus, the electrical live portion of the lamp base protrudes above the socket. Accidental contact with this portion and with an electrical ground can result in a serious shock.

Finally, the measurement of the higher socket temperature for the thermistor energy button and 100 watt lamp (see Table 3.2) presents a potential fire hazard. While the 105°C temperature does not exceed the UL safety code, some lamps may be used in enclosed fixtures that have no ventilation; in these applications a safe socket temperature could be exceeded resulting in a fire.

In the use of the energy button, the above three safety hazards must be recognized and avoided by the personnel that install or handle this equipment.

7. CONCLUSIONS

Light sources that can be employed in the same application must be assessed on total cost for the light delivered. The long-life lamps examined in this report show that the operating cost is the most important factor that will establish the cost effectiveness of a light source.

Energy buttons that drastically reduce the light output and the lamp efficacy are not cost effective even if the lamps last fifty times longer and the labor cost for each change is fifteen dollars.

The standard 100 watt, 120 volt lamp is the most cost effective of the incandescent lamps where the labor replacement cost is less than \$0.10, such as in the home.

The 100 watt long-life incandescent lamp is the best incandescent lamp replacement for the standard 100 watt (120 volt) incandescent lamp where the maintenance cost of replacement exceeds one dollar per change.

The most cost effective long-life replacement lamp for the standard 100 watt (120 volt) incandescent lamp is the adaptive fluorescent circline lamp. The cost of light with this source is significantly more cost effective than any long-life incandescent lamp or system evaluated in this report.

8. ACKNOWLEDGEMENT

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